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SEDIMENTATION IN ICE-DAMMED GLACIAL LAKE ASSINIBOINE, SASKATCHEWAN, AND CATASTROPHIC DRAINAGE DOWN THE ASSINIBOINE VALLEY

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ABSTRACT Ice-dammed glacial Lake Assiniboine covered approximately 1500 km² in eastern Saskatchewan at about 11,000 BP. Lithofacies in two cores from the lake basin were identified, correlated, and linked to paleolake strandlines and inflow and outflow channels discerned from aerial photos and surface mapping. Deeper lake stages are reflected by silt and clay varve deposition in the deepest part of the basin, whereas shallower stages are represented by fluctuating grain size and current-generated sedimentary structures in sediments nearer to where influxes of melt-water occurred. The stratigraphic record revealed six lake phases, beginning with a shallow period when water collected in the interlobate area between ice on the Duck Mountain Upland to the east and the Assiniboine Ice Lobe to the west. A rise in lake level to about 495 m occurred as the southern outlet was dammed by ice. After about 85 varve years, waters from the Porcupine Hills Upland to the north flooded into glacial Lake Assiniboine, perhaps as a result of the drainage of an ice marginal lake, causing erosion at the lake's southern outlet and a drop in lake level. A second major influx of water from the Porcupine Hills area, at least 20 varve years later, led to downcutting of the outlet and draining of Lake Assiniboine. Shallow and deep channels, streamlined hills, and scattered boulders adjacent to the now-entrenched Assiniboine valley at the former outlet of glacial Lake Assiniboine suggest that the lake drained catastrophically. Similar geomorphic features at sites downstream along the Assiniboine valley are also indicative of catastrophic flow, although only those areas north of the Qu'Appelle River spillway junction are predominantly attributed to outbursts from glacial Lake Assiniboine.

RÉSUMÉ La sédimentation dans le lac de barrage glaciaire Assiniboine (Saskatchewan) et la débâcle glaciaire le long de la vallée de l'Assiniboine. Le Lac Assiniboine, dans l'est de la Saskatchewan, avait une superficie d'environ 1500 km² vers 11 000 BP. Les lithofaciés de deux carottes recueillies dans le bassin du lac ont été identifiés, corrélés et reliés à des lignes de rivage du paléo-lac; les arrivées et les sorties d'eau ont été identifiées sur photographies aériennes et cartes de formations superficielles. Les stades de grande profondeur sont représentés par les dépôts de varves silteuses et argileuses dans les parties les plus profondes du bassin, tandis que les stades de moindre profondeur sont représentés par une granulométrie fluctuante et par les structures sédimentaires de courants situées près des entrées d'eaux de fonte. Les données stratigraphiques révèlent six phases lacustres, avec une première de faible profondeur dont l'eau provenait d'une région située entre le lobe glaciaire de Duck Mountain, à l'est, et le lobe Assiniboine, à l'ouest. Le niveau du lac a atteint 495 m lorsqu'un barrage glaciaire a fermé l'exutoire, au sud. Après 85 années varvaires, les eaux en provenance des Porcupine Hills, au nord, se sont déversées dans le Lac Assiniboine, probablement en raison de la vidange d'un lac de marge glaciaire, provoquant ainsi l'érosion de l'exutoire au sud du lac et l'abaissement du niveau. Un deuxième apport important en provenance des Porcupine Hills, survenu au moins 20 années varvaires plus tard, a provoqué une telle incision que le lac Assiniboine s'est vidé. Divers éléments et formes laissent croire que la vidange fut catastrophique. D'autres formes situées en aval le long de la vallée de l'Assiniboine témoignent aussi d'un écoulement catastrophique, bien que seules les parties situées au nord de la jonction avec le canal de trop plein de la rivière Qu'Appelle aient été attribuées à la débâcle du Lac Assiniboine.

ZUSAMMENFASSUNG Sedimentierung in dem glazialen Eisstausee Assiniboine, Saskatchewan, und Gletscheraustrich entlang dem Assiniboine-Tal. Der glaziale Eisstausee Assiniboine bedeckte circa 1500 km² im östlichen Saskatchewan um etwa 11 000 v.u.Z. In zwei Bohrkernen vom Seebecken wurden die Lithofazies identifiziert, korreliert und in Verbindung zu den Uferlinien des Paläosees gebracht; Wasserzufluß- und Wasserausflußkanäle wurden mittels Luftaufnahmen und Oberflächenkarten identifiziert. Stadien größerer Tiefe sind erkennbar an Schlamm- und Lehm-Warven-Ablagerung im tiefsten Teil des Beckens, wogegen seichter Stadien durch eine fluktuierende Kornverteilung und strombedingte Sedimentstrukturen in den Sedimenten, die dem Schmelzwasserzufluß näher waren, gekennzeichnet sind. Der stratigraphische Beleg läßt sechs Seenphasen erkennen, beginnend mit einer seichten Periode, als Wasser sich in dem Gebiet zwischen der Eislobe von Duck Mountain Upland im Osten und der Assiniboine-Eislobe im Westen ansammelte. Der Wasserspiegel des Sees stieg auf etwa 495 m an, als der südliche Ausläufer durch Eis gestaut wurde. Nach etwa 85 Warven-Jahren ergoß sich das Wasser vom Porcupine Hills Upland nordwärts in den glazialen Assiniboine-See, vielleicht infolge der Entwässerung eines Eisrandsees, und bewirkte eine Erosion am südlichen Seeausfluß und eine Senkung des Wasserspiegels. Ein zweiter bedeutender Zufluß von Wasser vom Gebiet der Porcupine Hills, mindestens 20 Warven-Jahre später, führte zu einem Einschnitt des Ausflusses, so daß der Assiniboine-See sich leerte. Flache und tiefe Furchen, stromförmige Hügel und verstreute Blöcke neben dem jetzt an dem früheren Ausfluß des Assiniboine-Sees eingegrabenen Assiniboine-Tal lassen vermuten, daß der See sich katastrophal leerte. Ähnliche geomorphologische Formen talabwärts entlang dem Assiniboine-Tal weisen auch auf ein katastrophales Abfließen, wenn auch nur die Gebiete nördlich des Zusammenflusses des Qu'Appelle River mit der Überlaufrinne den Ausbrüchen vom glazialen Assiniboine-See zugeschrieben werden.

INTRODUCTION

Late in the Lockhart Phase of glacial Lake Agassiz, meltwater drainage in the Canadian Prairies was routed through the Assiniboine and Qu'Appelle spillways (Clayton and Moran, 1982). A coarse-grained underflow fan was deposited in glacial Lake Agassiz at the termination of the Assiniboine spillway near Brandon, Manitoba (Fig. 1). Fan-delta construction probably began at about 11,200 BP and ended when the lake fell below the Campbell level in response to the opening of Lake Agassiz's eastern outlets shortly after 11,000 BP. Flood deposits in the Assiniboine fan-delta (Sun, 1993) and catastrophic flood geomorphology in the Assiniboine valley upstream (Teller *et al.*, 1990) indicate that several major pulses of water entered Lake Agassiz from this spillway system.

One source of water contributing to the formation of erosional and depositional features associated with the Assiniboine valley as far downstream as the fan-delta may have been the abrupt drainage from glacial Lake Assiniboine, which formed at the upstream end of the Assiniboine valley along the margin of the Laurentide Ice Sheet (Fig. 1; Klassen, 1975; Kehew and Lord, 1987; Wolfe, 1993). Recent work by Wolfe and Teller (1993) focused on the stratigraphic character of 106 varves which were used to reconstruct the paleohydrology of Lake Assiniboine. This paper considers the sedimentary record revealed from two long cores, one which includes the thick sequence of varved sediments, to relate the history of Lake Assiniboine to regional events during the last deglaciation.

STUDY AREA

Located in eastern Saskatchewan, most of the Lake Assiniboine Plain is relatively flat except for late glacial and postglacial river dissection. Several streams meander across the former lake basin, including the Assiniboine River, Whitesand River, and Little Boggy Creek; these meet and flow through the Assiniboine valley south of Kamsack (Fig. 2). The modern Swan River occupies an 80-m-deep, 1-km-wide spillway to the north that bypasses the Lake Assiniboine Plain and flows to the northeast. The ancestral Assiniboine and Whitesand Rivers appear to have provided most of the coarse sediment to glacial Lake Assiniboine (Fig. 2).

METHODS

From a detailed geomorphological study of aerial photos and topographic maps, accompanied by field mapping, strandlines and channels in the glacial Lake Assiniboine region (Fig. 2), and late glacial meltwater flow features downstream (south) along the Assiniboine valley from Kamsack, Saskatchewan to Virden, Manitoba were identified (Fig. 1).

Two sediment cores (Assin-1 and Assin-2) were retrieved in the Lake Assiniboine basin (Fig. 2) using a truck mounted, mechanical hollow stem auger drilling system. About 50 m of core were recovered in 7-cm-diameter and 0.6-m-long Shelby tubes by this process. In the lab, the sediment was extruded from the Shelby tubes using a hydraulic piston, placed in split 0.6 m long plastic tubes, covered in heavy plastic bags, and labelled. Cores were scraped down to a

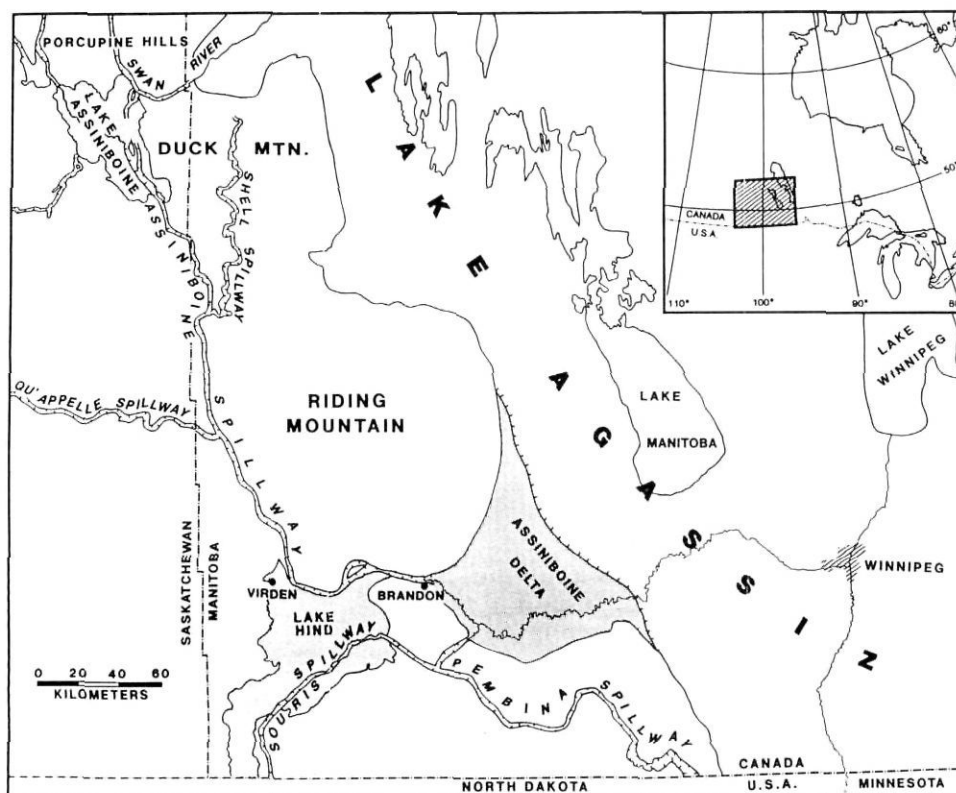


FIGURE 1. Location of glacial Lake Assiniboine and major spillways eroded during the last deglaciation. Glacial Lake Hind is also shown in addition to the main part of the Assiniboine fan-delta which was deposited into Lake Agassiz by meltwater floods through the Assiniboine-Qu'Appelle spillway system.

Localisation du Lac Assiniboine et des principaux canaux de trop plein érodés au cours de la dernière glaciation. On montre également le Lac Hind ainsi que le cône de déjection de l'Assiniboine mis en place dans le Lac Agassiz par des crues d'eaux de fonte qui ont emprunté le réseau d'évacuation Assiniboine-Qu'Appelle.

flat surface and then left uncovered for approximately 48 hours which, because of differential drying, brought out subtle sedimentary features. All cores were then photographed and described in detail, and graphic logs were prepared at a scale of 1:2 (see Wolfe, 1993).

Samples from the cores were generally collected at 0.6 m intervals except in the varved interval of core Assin-1 where a much more detailed sampling approach was used (Wolfe and Teller, 1993). All samples were analyzed for mean diameter using the laser-equipped Brinkmann Particle Size Analyzer 2010 at the University of Manitoba. Milligram-size samples were immersed in 2% Calgon solution, shaken, and covered overnight to allow the sediment to disperse. Immediately prior to grain size analysis, each sample was placed in an ultrasonic bath for 2 minutes to permit further disaggregation. Several drops of the slurry were transferred to a cuvette, again diluted with 2% Calgon solution, and placed in the Brinkmann electro-optical unit for analysis.

Most of the sediment from Assin-1 consists dominantly of silt and clay and was analyzed to 60 μm at 0.2 μm resolution. Because of the coarser nature of Assin-2 and unit 1 from Assin-1, these samples were analyzed at a resolution of 0.5 μm to 150 μm . However, analyses from sandy units 3 and 5 in core Assin-2 display truncated particle size distributions indicating that the mean diameter of these samples is likely underestimated (Wolfe, 1993).

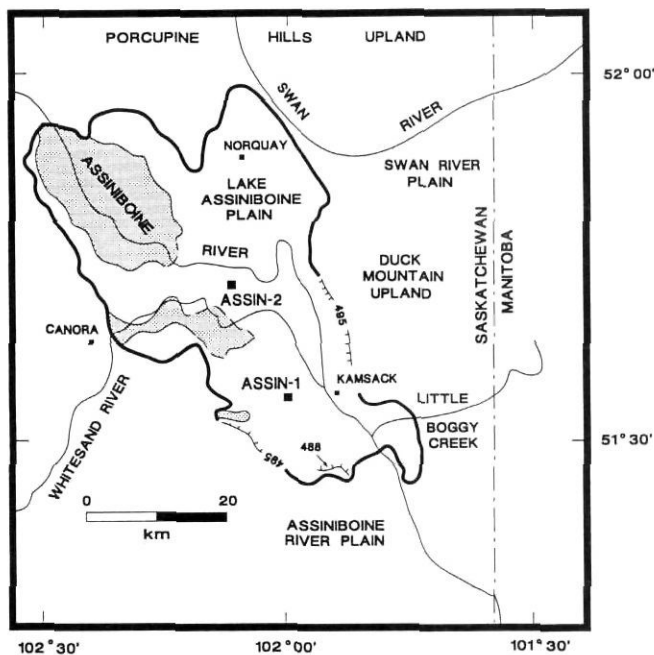


FIGURE 2. Generalized map of modern drainage system, physiography, coarse grained glaciolacustrine sediments (stippled zones) deposited by former inflowing channels, and strandlines (hatched lines) with elevations (m) described in Wolfe and Teller (1993). Included are locations for the Assin-1 and Assin-2 cores.

Carte montrant le réseau de drainage moderne, la physiographie, les zones de sédiments glacio-lacustres grossiers (trames) charriés par d'anciens chenaux et l'altitude des lignes de rivage (hachures) (de Wolfe et Teller, 1993). La carte montre également la localisation des sondages Assin-1 et Assin-2.

SEDIMENTARY RECORD OF GLACIAL LAKE ASSINIBOINE

Water well log data indicated that thick deposits of clay were located in the southern part of the basin (Wolfe, 1993). A few exposures of varved silt and clay were also found in this area (Wolfe and Teller, 1993). To obtain a complete sequence of the varved interval, core Assin-1 was obtained from this region.

Widespread sand and gravel deposits located on the western side of the basin suggested that precursors to the Assiniboine and Whitesand Rivers were major sediment suppliers to glacial Lake Assiniboine. To investigate the temporal relationship of these inflows with lake history, core Assin-2 was taken from the central part of the basin near to the sediment sources.

ASSIN-1

A continuous 22.3 m core of dominantly silt and clay was recovered in Assin-1 (Fig. 3). Four units are distinguished. At the base of the sequence, between 22.3 m and 20.3 m, is a poorly sorted diamicton (unit 1) composed of clay, silt, and sand-sized grains with pebbles (<5%), granules (15%), and granule- to pebble-sized, rounded clay clasts (15%). Only one sample was taken from this unit and analysis of the matrix revealed a mean grain size in the medium silt range. No bedding was observed. Poor sorting and dominantly massive structure in unit 1 are features characteristic of deposition directly by ice, although clay clasts suggest resedimentation and are perhaps indicative of a debris flow or flow till.

Unit 2 in Assin-1 is 5.3 m thick and is separated from unit 1 by a sharp, irregular contact. The unit is dominantly massive, very fine to medium grained silt. Some sedimentary structures are present, including rare 5-20 cm cross-laminated beds and zones of lenticular bedding containing 0.2-0.5 cm thick lenses of silt (Fig. 4a). In the upper half of the unit are thin beds of diamicton which are massive, poorly sorted silt containing pebbles (5%) and granules (15%); some of the granule- to pebble-sized clasts are composed of clay fragments that are rounded. This sediment occurs in beds 0.5 to 13.0 cm thick with sharp, irregular upper and lower contacts (Fig. 4b).

Massive, non-rhythmic, relatively well sorted, clayey silt in unit 2 suggests subaqueous sedimentation. Structureless sediment may be products of (1) sediment disturbance at the lake floor as a result of wave action or (2) constant, year-round vertical mixing of lake water and a continuous flux of sediment settling onto the lake floor (Smith and Ashley, 1985). In particular, absence of any seasonal dark, clay-rich laminations, typical for annual deposits such as those in unit 3, is perhaps because the fine clay that settled during ice-covered conditions in the winter was disturbed, resuspended, and mixed with coarser sediment during spring turnover or strong wind events.

Periodic, high-discharge events, likely reflective of significant melting periods or storms, were responsible for the deposition of cross-laminated and lenticular bedded (Fig.

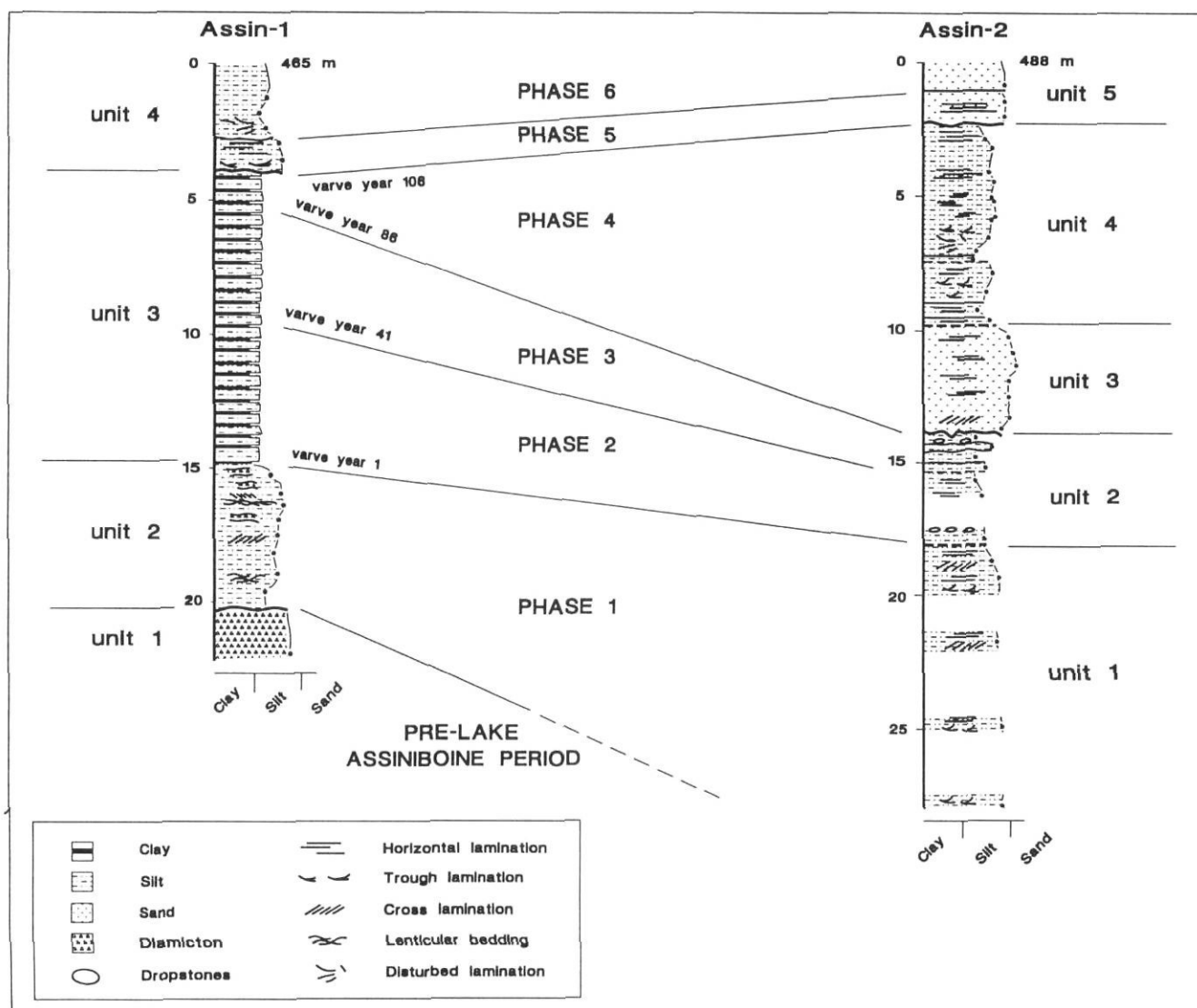


FIGURE 3. Subsurface stratigraphy, correlation, and lake phase designation in the glacial Lake Assiniboine basin. Note that elevation of cores differs by 23 m. Samples analyzed for mean grain size are plotted except in unit 3 of core Assin-1. Number and thickness of couplets illustrated in unit 3 of Assin-1 core are not to scale. Several intervals near the bottom of Assin-2 core were not recovered.

Stratigraphie, corrélation et désignation des différentes phases dans le bassin du Lac Assiniboine. Notez la différence de 23 m entre l'altitude des deux carottes. Les échantillons analysés pour leur granulométrie ont été reportés sauf pour l'unité 3 de la carotte Assin-1. Le nombre et l'épaisseur des couplets illustrés dans l'unité 3 de Assin-1 ne sont pas à l'échelle. Plusieurs intervalles près de la base de Assin-2 n'ont pas été récupérés.

4a) medium grained silt that interrupt the otherwise, monotonous, low energy clayey silt deposition. The cross-laminations and medium grained silt lenses provide evidence for relatively strong underflow currents. The isolated nature of these lenses of silt indicate that the silt supply was low (Reineck and Singh, 1980).

Sharp lower and upper contacts of beds of diamicton within clayey silt (Fig. 4b) in the upper half of unit 2 suggest that deposition of this material began and terminated abruptly. These beds may represent debris deposited by the melting of icebergs floating on Lake Assiniboine or, alternatively may have been deposited by debris flows.

Unit 3 consists of 106 alternating thick (3.4-16.4 cm), light coloured beds and thin (0.1-3.9 cm), dark coloured

beds (Fig. 4c). This is the thickest unit in Assin-1, spanning 10.9 m from a depth of 14.9 m to 4.0 m, and is separated from unit 2 by a gradational contact. Light coloured beds are characterized by mean grain sizes ranging from very fine to fine grained silt, while the mean grain size in dark beds is primarily clay to very fine silt. Contacts between the beds are generally sharp. Thin laminations of poorly sorted silt and clay containing occasional granules are present in the coarser bed of many couplets in the lower part of the sequence. Bedding is horizontal, although there are some cross- and deformed laminations in the silt beds. Horizontal laminations are also sometimes visible in the clay beds. Bed thickness measurements revealed a thinning upward trend. However, near the top of the sequence at about varve year 86, silt bed and total couplet thicknesses

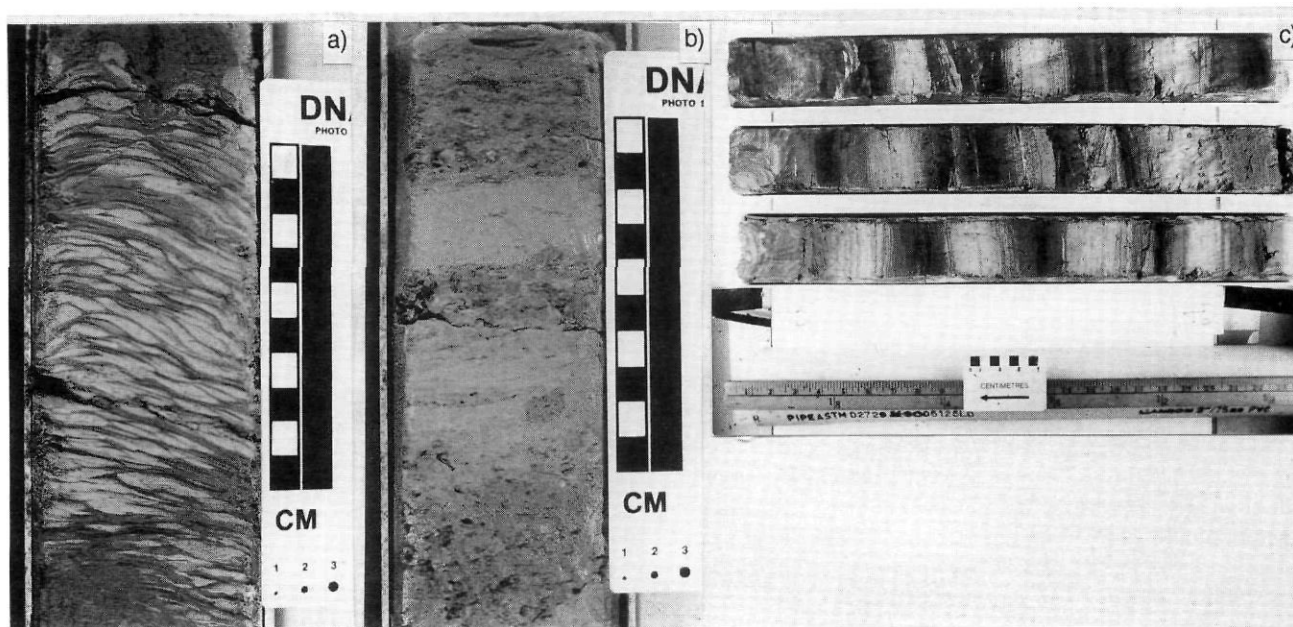


FIGURE 4. Sediment from Assin-1 core. a) Photo shows 17 cm zone of lenticular bedding in unit 2 at about 16.5 m depth. b) Unit 2 at about 15.2 m depth. Structureless beds of diamicton are present within massive to poorly laminated fine grained sediment. c) Unit 3 between 11.9 and 13.7 m depth. Photo shows portion of rhythmically bedded sequence. See Wolfe and Teller (1993) for more detailed photographs of individual couplets.

Sédiments de la carotte Assin-1. a) La photo montre une zone de 17 cm de stratification lenticulaire à une profondeur d'environ 16,5 m de l'unité 2. b) L'unité 2 à environ 15,2 m de profondeur. Des lits non structurés de diamicton se répartissent dans le sédiment à grains fins de structure massive à faiblement laminée (feuilletés). c) L'unité 3, entre 11,9 et 13,7 m de profondeur. La photo montre une partie de la séquence à stratification rythmée. Voir les photos détaillées de couplets individuels dans Wolfe et Teller (1993).

increase to varve year 98 and then remain relatively constant while clay bed thickness continues to decrease.

Detailed interpretations of unit 3 have been presented elsewhere (Wolfe, 1993; Wolfe and Teller, 1993). Briefly, several sedimentological features indicate that the 106 couplets represent varve deposits, including frequent sharp basal and upper contacts of the silty bed, occasional silt and clay laminations indicative of discrete current fluctuations within the summer and winter, and occasional ice-rafted material in the silty bed. Their uniform to gradually varying thickness also argues for an annual origin.

Silt and clay bed thickness variations were largely controlled by the proximity of meltwater inflow channels and lake depth (Wolfe and Teller, 1993). The thickest silt and thickest clay beds in the varved sequence occur in the lower part (varve years 1-40), probably as a result of close proximity of the ice margin. Silt bed and total couplet thicknesses become substantially thinner from about varve year 41 to 85. These varves were deposited when the ice margin was more distal. The increase in silt bed and total couplet thickness and the decrease in clay bed thickness beginning near varve year 86 is interpreted to have been a result of decreasing water level. This would have increased energy on the lake floor and have caused resuspension of already-deposited silts and clays in the shallowest areas of the basin. As well, there would have been an increase in sedimentation of more silty sediment (and, potentially, more total sediment) at the Assin-1 core site because of its increasingly more proximal location to inflow channels as a result of lowering lake level.

A sharp contact divides two beds in unit 4. The lower 1.3 m is composed almost exclusively of silt and is separated from unit 3 by a sharp contact. Horizontal laminations occur throughout this part of the unit and trough cross-laminations are present at the base. A sample in the trough cross-laminated zone generated the coarsest mean grain size in the entire core ($22.5 \mu\text{m}$). Grain size is slightly finer in the upper horizontally laminated zone. The upper 2.7 m of unit 4 is clayey silt and is mottled or poorly laminated. Folded laminations were also observed in this part of the unit.

Trough cross-laminated silt beds near the base of unit 4, which are nearly devoid of clay, likely reflect traction current deposition by relatively strong underflow currents (Smith, 1978). The overlying horizontally laminated silt indicates that suspension sedimentation in the lake eventually became dominant. Overall, these sediments are coarser than unit 3 suggesting an increase in energy, and the sharp and irregular lower contact indicates that erosion occurred prior to deposition of this unit. Termination of the underlying varved sequence (unit 3), the coarser grained nature of the deposit, and presence of underflow current structures are suggestive of a comparatively high energy event.

Clayey silt in the upper part of unit 4 suggests that quiet water conditions resumed. Unlike unit 3, however, this sediment is non-rhythmic and poorly laminated or deformed. Similar to unit 2, absence of seasonal dark, clay-rich laminations suggests that fine clay that settled was disturbed and resuspended during seasonal turnover or strong wind events. Physical mixing also resulted in poorly laminated

sediment. Presence of folded laminations may indicate slumping along an unstable lake floor. Lack of ice-rafted debris suggests that the ice margin had retreated from the edge of the lake.

Vertical Relationships

The sequence in core Assin-1 appears to represent the evolution of an ice-marginal lake. Following retreat of ice from the basin, the early phase of the lake is marked by rapid sediment influx punctuated by deposition of ice-rafted detritus and/or debris flows (unit 2). A lower energy phase ensued and deposition of varved silt and clay occurred (unit 3) likely as a result of increasing water depth which limited wave induced disturbance at the lake floor. Higher energy deposition is reflected by the coarser sediment in the lower part of unit 4 and by the abrupt termination of the varved sequence. These sediments represent the final major influx of water into the lake. Finally, glacial Lake Assiniboine sedimentation ended when the lake drained, a century or two after the first phase of the lake had begun.

ASSIN-2

Assin-2 was drilled to a depth of 28 m although several metres of core in the lower half were not recovered (Fig. 3). This core is located nearer to the glacial river systems that carried sediment to Lake Assiniboine than the Assin-1 core

(Fig. 2). This is reflected in the overall larger grain size in the Assin-2 core and greater frequency of various current-generated sedimentary structures such as ripples and cross-laminations. Assin-2 is subdivided into five units.

Unit 1 (28.0 to 18.0 m) is primarily silt and contains abundant sedimentary structures including horizontal, planar, and trough cross-lamination (Fig. 5a), and type A climbing ripples (Smith and Ashley, 1985). There is no significant vertical change in sediment type nor sedimentary structures through this unit, although mean grain size does vary from coarse silt at the base to medium silt at the top.

Abundant current structures in silty unit 1 indicate that traction currents, perhaps density underflows, deposited these sediments (Smith and Ashley, 1985). Trough cross-laminations are due to bottom-hugging flows (Fig. 5a) and type A climbing ripples suggest high sediment supply/current velocity ratio (Smith and Ashley, 1985).

Unit 2 (18.0 to 13.9 m) is finer grained than unit 1 and contains fewer sedimentary structures. The contact with unit 1 is gradational over 5 cm. Mean grain size for most of this unit is within the fine silt range except for two massive, medium grained silt beds that occur near the top of the interval. Laminations are visible, mainly at the base of this unit, and contain clasts of subrounded silt and clay. Isolated

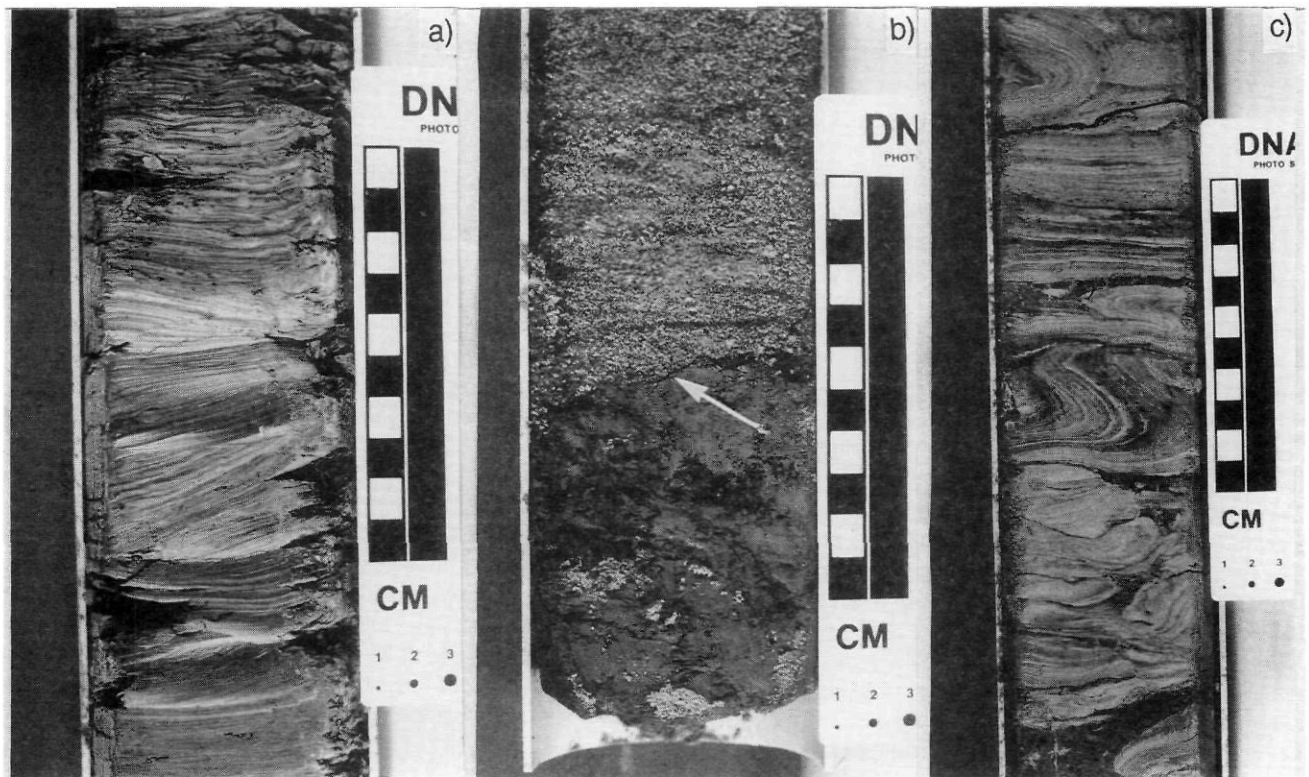


FIGURE 5. Sediment from Assin-2 core. a) Unit 1 at a depth of about 18.3 m. Planar and trough cross-bedding occur in silty sediment. b) A sharp and irregular contact separates unit 3 from finer grained unit 2 at about 13.7 m depth. c) Photo illustrates complexly laminated and folded silt and clay sediment in unit 4 at about 7.0 m depth.

Sédiments de la carotte Assin-2. a) L'unité 1, à environ 18,3 m de profondeur. Stratification entrecroisée plane et en creux dans le silt. b) Un contact net et irrégulier sépare l'unité 3 de l'unité 2 à grains fins, à 13,7 cm de profondeur. c) La photo montre bien le sédiment de silt et d'argile de l'unité 4 à laminations et à plis complexes, à environ 7,0 m de profondeur.

dropstones are embedded in the fine silt at the base and near the top of this interval.

The decrease in grain size from unit 1 to unit 2 suggests current strength declined. The gradational lower contact is indicative of a transition in depositional conditions. Occasional horizontal laminations in the otherwise massive sediment of this unit suggests relatively quiet water conditions in an ice-marginal glaciolacustrine environment, except for occasional events of ice-rafting. The massive portion of unit 2 is likely due to mixing of sediment on the lake floor, while laminations suggest episodes when mixing did not occur. Absence of varves in this unit is attributed to mixing and resuspension of clay sized material, although a relatively constant year-round influx of silty sediment to this site from subglacial meltwater may have been the cause.

Relatively coarse beds near the top of unit 2 indicate higher energy flow events, perhaps induced by storms or major melting events. Alternatively, this site may have become more proximal to the source (*i.e.* ice margin, mouth of river) at this time.

Unit 3, 13.9 m to 9.4 m in depth, is in sharp contrast to the previously described units. Core description indicated average grain size is in the fine to medium sand range. Mean grain size depicted in Figure 3 are minimal estimates because samples were analyzed to only 150 μm . This unit is separated from unit 2 by a sharp, irregular contact (Fig. 5b). Scattered within the middle of this unit are several granule-sized fragments of lignite. Tabular sets of cross-beds (up to 8 cm thick) are visible at the base but stratification is vague throughout the rest of the unit. Poor core quality prevented more detailed identification and description of sedimentary structures.

A marked increase in grain size to fine-medium grained sand, an erosive lower contact (Fig. 5b), and discernible cross-beds at the base of unit 3 suggest deposition from traction currents. This unit may represent (1) material deposited subaqueously by surge currents generated by basin slope failure, (2) shifting of distributaries emanating from the Assiniboine River which lay to the northwest, or (3) sediments deposited by a major influx of water entering Lake Assiniboine. The thickness of the unit (4.1 m) is suggestive of an event more significant than an average storm or slump. Laminations of fine sediment or abrupt contacts would be expected if the sediment influx was a result of changing sediment dispersal patterns, storms, or slumping. Constant grain size and an apparent lack of stratification may be due to rapid deposition, which is consistent with a major influx of water entering Lake Assiniboine.

Unit 4 spans 7.1 m from a depth of 9.4 m to 2.3 m. This unit is variable in grain size and consists of interbedded, horizontally laminated silt and massive clayey silt near the bottom to horizontally laminated silt in the upper half. The lower part of the interval also contains planar and trough cross-laminations composed of silt and sand that are occasionally folded (Fig. 5c). Contacts between the planar, trough, horizontal, and massive beds are usually sharp.

Although finer grain size indicates relatively quieter water conditions prevailed after deposition of unit 3, several characteristics suggest inflow events responsible for the sediments of unit 4 varied in energy. These include sharp contacts between silty and clayey interbeds and occasional planar and trough cross-laminations. In addition, complexly laminated sediment (Fig. 5c) is likely the result of liquefaction generated when relatively coarse sediment is rapidly deposited on water-saturated fine-grained material (Reineck and Singh, 1980).

Unit 5 is composed primarily of sand separated from unit 4 by a sharp contact. Similar to unit 3, mean grain size analyses from this unit represent minimal estimates although core description indicates that the lower 1.4 m of the unit is very fine grained sand to sandy silt and the upper 0.9 m is fine grained, very well sorted sand. These two beds are separated by a sharp contact. Horizontal laminations are visible near the base of this unit, otherwise the sand appears massive.

Sedimentologically, unit 5 is similar to unit 3. An erosive lower contact, sharp increase in grain size and generally massive sediment indicate rapid deposition in relatively high energy conditions. Improved sorting in the upper part of unit 5 and similarity to surficial aeolian deposits (Wolfe, 1993), suggests that this portion has been reworked by wind.

Vertical Relationships

Most conspicuous in the Assin-2 core are two prominent sand units (units 3 and 5, Fig. 3) which have several similarities, including an erosive basal contact, comparable grain size, and massive nature. Studies of glacial lake outbursts in the northern Great Plains of the United States and Canada have shown that floods advanced from basin to basin, triggering erosion at outlets, and causing lakes to drain in sequence (Kehew and Lord, 1987; Kehew and Teller, 1994). Sand was deposited in downstream ice-marginal basins that were inundated by the floods (Kehew and Lord, 1987; Lord, 1991). Sandy units 3 and 5 are interpreted as sediments deposited by large, short duration inflows of water to glacial Lake Assiniboine. This may have occurred by the abrupt release of meltwater stored in other ice-marginal lakes to the north such as glacial Lake Melfort (Moran, 1969), during an anomalous period of runoff, or by the release of stored subglacial waters (*cf.* Shaw and Gilbert, 1990; Sharpe and Cowan, 1990).

There is no evidence of subaerial exposure immediately following deposition of unit 3, suggesting that the first major influx did not cause Lake Assiniboine to completely drain. Therefore, much of the sediment that entered Lake Assiniboine was retained within the basin as the current dissipated, and the accumulation of finer lacustrine sediments (unit 4) resumed after the first flood event. In contrast, no fine grained sediments overlie the second coarser unit (unit 5); instead it is succeeded by subaerially deposited sediment, suggesting that the lake drained at this time.

DOWNSTREAM FLOOD GEOMORPHOLOGY

Previous geomorphological and sedimentological studies of the Assiniboine valley have been presented by Klassen (1972, 1975, 1983). Our investigation focused on the identification of catastrophic flood features along the Assiniboine valley, using the model described by Kehew and Lord (1986, 1987), which may be associated with the abrupt drainage of glacial lakes Assiniboine and others.

GENERAL FEATURES

Several characteristics of the Assiniboine valley are consistent with Kehew and Lord's (1986, 1987) model of spillway morphology: (1) the modern Assiniboine River is underfit in a deeply entrenched valley, (2) the Assiniboine valley lacks significant tributaries aside from similar spillways such as the Qu'Appelle, Shell, and Birdtail Rivers (Fig. 6), (3) the valley width and depth is constant from the outlet of Lake Assiniboine to where it entered Lake Agassiz near Brandon, Manitoba, and (4) there is a scoured region (outer zone) in many places bordering the now-entrenched inner channel (Fig. 7).

INNER CHANNEL

Features of the inner channel are also similar to those described by Kehew and Lord (1986, 1987) including (1) the inner channel possesses a trench-like shape and its width is uniform, (2) the dimensions of the valley (2 km wide and 60 m deep) are within the typical range of other Great Plains spillways (1-3 km wide, 25-100 m deep), and (3) erosional residuals are found in the main inner channel in the outlet area of Lake Assiniboine.

OUTER ZONE

Characteristic flood features in the outer zone have been recognized along various segments of the Assiniboine valley from the Lake Assiniboine outlet to Virden, Manitoba (Figs. 6 and 7) and include abandoned channels (Fig. 8a), streamlined erosional residuals (Fig. 8b), erosional scarps that parallel the main inner channel, and boulder lags. Hummocky topography commonly lies outside of the water affected outer (and inner) zones, beyond the erosional scarp.

DEGLACIAL HISTORY

OVERVIEW

Datable material was not found in the sediments of the Lake Assiniboine basin and, therefore, the age of the lake cannot be determined with certainty. Fenton *et al.* (1983) indicated that the Assiniboine spillway, through which Lake Assiniboine drained, was deglaciated by about 11,200 BP. Continued retreat of the ice margin to the northeast allowed glacial Lake Swan to form along the Swan River valley between Duck Mountain and Porcupine Hills, which Nielsen (1988) concluded drained eastward through the Swan River to Lake Agassiz by 10,800 BP. Thus, shortly after the start of the Moorhead low water stage of glacial Lake Agassiz at 11,000 BP (Fenton *et al.*, 1983), the Swan River valley had entrenched itself below the level of glacial Lake Assiniboine,

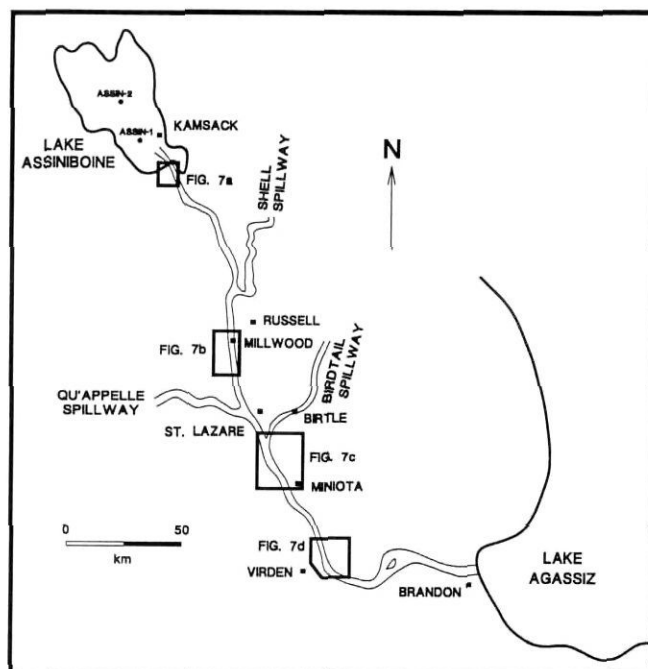


FIGURE 6. Glacial Lake Assiniboine, the Assiniboine valley, and glacial Lake Agassiz. Also shown are coring locations in the Lake Assiniboine basin and where the Shell, Qu'Appelle, and Birdtail valleys join the Assiniboine valley. Boxed areas are locations for Figure 7a, b, c, and d.

Le Lac Assiniboine, la vallée de l'Assiniboine et le Lac Agassiz. Localisation des sites de forage dans le bassin du Lac Assiniboine et les jonctions des vallées des rivières Shell, Qu'Appelle et Birdtail avec l'Assiniboine. Les rectangles localisent les figures 7a, b, c et d.

and flow from this valley bypassed the old Lake Assiniboine basin. These studies suggest that the sediments of glacial Lake Assiniboine were deposited between 11,200 and 10,800 BP.

PHASE 1

Glacial Lake Assiniboine first formed as ice retreat allowed meltwater to collect in the topographical depression between the Assiniboine and Duck Mountain Ice Lobes (Klassen, 1975; Fig. 9a). Overflow was south along the western side of Duck and Riding Mountain, probably in a shallow precursor of the Assiniboine valley. Shallow water conditions in the lake during this phase are suggested by the lowermost water-deposited sediment in the Assin-2 and Assin-1 cores. In unit 1 of the Assin-2 core (Fig. 3), silt containing sedimentary structures such as trough cross-laminations and climbing ripples are indicative of traction-current deposited sediments. The equivalent bed in the Assin-1 core, albeit in a location more distal to the inflow of runoff and therefore thinner, is occasionally cross-laminated, non-varved clayey silt, with intermittent beds of poorly sorted diamicton (unit 2; Fig. 3). During this time, the Laurentide ice margin lay nearby supplying meltwater runoff particularly to the northern part of the lake (Wolfe, 1993), and was perhaps in contact with the lake near core site Assin-1 where icebergs carried detritus offshore (Fig. 9a). This phase may have spanned a very few years.

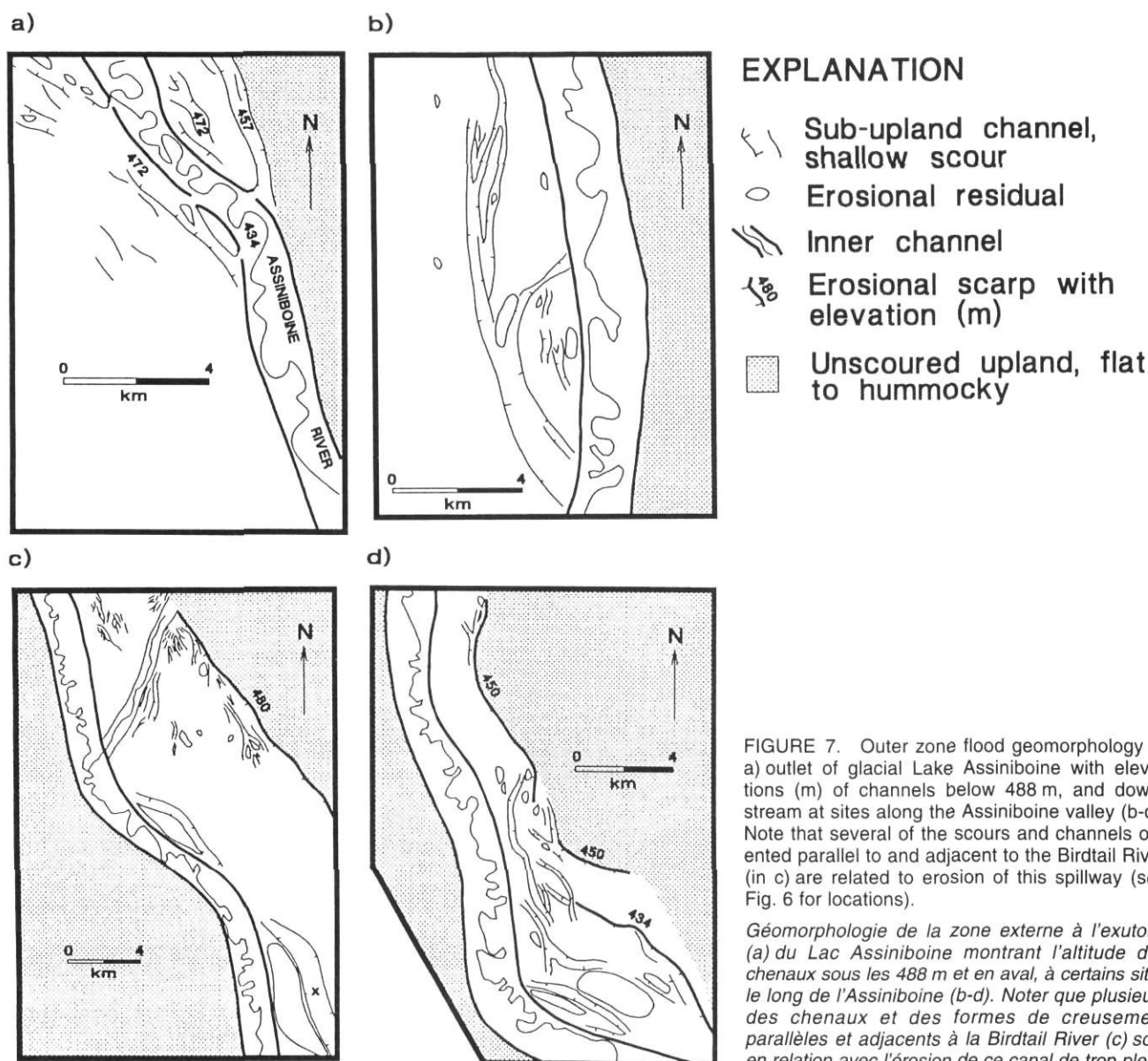


FIGURE 7. Outer zone flood geomorphology at a) outlet of glacial Lake Assiniboine with elevations (m) of channels below 488 m, and downstream at sites along the Assiniboine valley (b-d). Note that several of the scours and channels oriented parallel to and adjacent to the Birdtail River (in c) are related to erosion of this spillway (see Fig. 6 for locations).

Géomorphologie de la zone externe à l'exutoire (a) du Lac Assiniboine montrant l'altitude des chenaux sous les 488 m et en aval, à certains sites le long de l'Assiniboine (b-d). Noter que plusieurs des chenaux et des formes de creusement parallèles et adjacents à la Birdtail River (c) sont en relation avec l'érosion de ce canal de trop plein.

PHASE 2

Sedimentation changed following the first phase of glacial Lake Assiniboine. Couplets of silt and clay (varves) were deposited in the deepest part of the basin. The thickest 40 varves at the base of unit 3 in core Assin-1 (Fig. 3) were deposited at this time because the site was near a temporary point of sediment influx on the western side of the lake (see esker, Fig. 9b). Ice probably still bordered most of the lake, although a weakly developed strandline in a few places at 495 m (Fig. 9b) has been correlated with this phase of the lake (Wolfe and Teller, 1993).

Deposition of varved silt and clay occurred (unit 3, Assin-1) likely as a result of increased water depth which limited wave induced disturbance at the lake floor, thus preserving clay that settled during annual periods of ice cover. Because the Assin-2 site was in shallower water, varves did not develop and instead, uniformly silty sediment was de-

posited. However, an upward decrease in (1) grain size from medium-coarse grained silt to fine-medium grained silt and (2) traction current sedimentary structures from unit 1 to unit 2 indicates a trend toward lower energy conditions, consistent with a rise in lake level.

This rise in lake level may have occurred in response to an ice readvance from the Duck Mountain Upland. Supporting evidence comes from the Little Boggy Creek valley at the southern end of glacial Lake Assiniboine (Fig. 2), which has been partly filled by hummocky drift. The surface on which this drift lies is now a dissected valley floor at 450 m in elevation, which is well below the estimated level of the lake during the earliest stage (Wolfe, 1993). Thus, initial overflow may have been through the Little Boggy Creek valley until ice from Duck Mountain readvanced over this outlet, forcing the lake to rise during Phase 2 to the 495 m level (Fig. 9b).

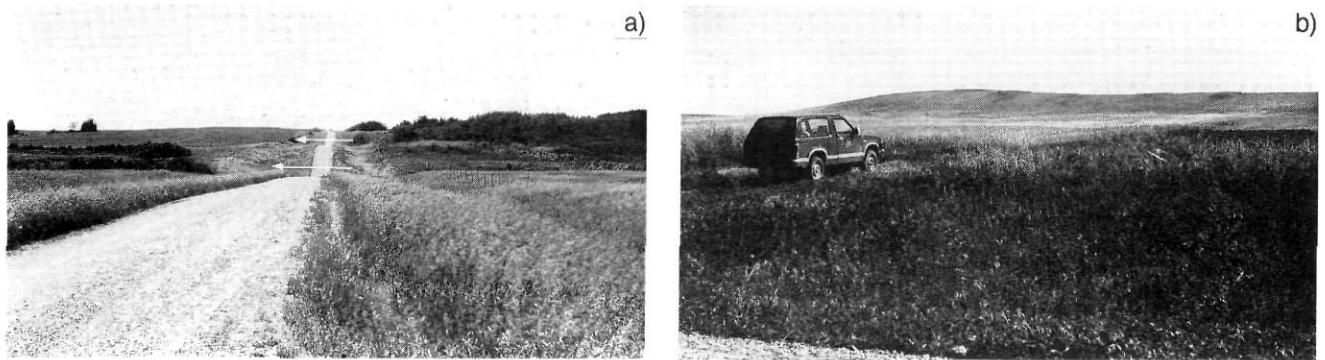


FIGURE 8. Examples of typical outer zone flood geomorphology. a) Multi-level, shallow scour channels at the outlet of glacial Lake Assiniboine. Flow was toward the left (south). b) 8.5 m high erosional residual from area in Figure 7b. Flow was to the right (south).

Exemples de géomorphologie caractéristique de la zone externe d'inondation. a) Chenaux de creusement peu profonds à multiples niveaux, à l'exutoire du Lac Assiniboine. L'écoulement se faisait vers la gauche (sud). b) Colline résiduelle de 8,5 m de haut de la région de la figure 7 b. L'écoulement se faisait vers la droite (sud).

Outflow may have occurred around this ice dam in a channel at 495 m towards Lake Agassiz (Fig. 9b). Identification of the geomorphic record left by this "normal" outflow, downstream from Lake Assiniboine, is uncertain because of subsequent modification by the catastrophic draining of Lake Assiniboine (see Phase 5 below).

PHASE 3

A decrease in silt bed and couplet thickness from varve years 41-85 in unit 3 of core Assin-1, suggests that this coring site became more distal to the sediment influx (Wolfe and Teller, 1993). Active margin retreat of the Assiniboine Ice Lobe to the west allowed the Whitesand River to carry meltwater and deposit sand, gravel, with minor silt and clay where it entered Lake Assiniboine (Fig. 9c). Abundant kettle lakes in the area south of where the Whitesand River entered Lake Assiniboine suggests that stagnant ice remained.

Although decreasing sediment concentration in the water column could also have produced the stratigraphic changes in the varved interval, deposition of medium grained silt beds in the upper part of unit 2, core Assin-2, which interrupt the fine silt prevalent in the lower part of this unit, is consistent with the shift in sediment sources and this site's more proximal location to the Whitesand and Assiniboine River influxes (Fig. 9c).

PHASE 4

Features in unit 3 of the Assin-2 core, including an abrupt increase in grain size from clayey silt to fine-medium grained sand, plus a sharp, erosive lower contact, suggest that a new influx of sediment entered Lake Assiniboine at this time. (Erosion at the top of unit 2 in Assin-2 as a result of this inflow, might explain why the Assin-2, Phase 3 interval is thinner, compared to correlated strata in the Assin-1 core (Fig. 3), despite its closer proximity to the main sediment sources.) Similar grain size throughout unit 3 of core Assin-2 and weak stratification implies that these sediments were deposited rapidly. The most likely source for this inflow is drainage from the Porcupine Hills Upland area, to the north of glacial Lake Assiniboine, where ice or meltwater may

have transported this lignite-bearing sediment from the Cretaceous Mannville Group of central Saskatchewan (Smith, 1989). This inflow probably initiated downcutting at the outlet of Lake Assiniboine which eventually stabilized at 488 m (Fig. 9d).

Directly overlying the sandy sediments in unit 3 of core Assin-2 are 7.1 m of interbedded silt and clayey silt beds, which grade upward to silt in the upper half of the interval (unit 4; Fig. 3). Both planar and trough cross-beds occur in the lower part of the unit. These current structures, which are absent in unit 2 of this core, are consistent with a fall in lake level after the inflow that deposited sandy unit 3 and are correlated to shallow water varve years 86-106 in the Assin-1 core (Fig. 3; Wolfe and Teller, 1993).

PHASE 5

The varved sediments of unit 3 in the Assin-1 core are abruptly overlain by trough cross-laminated and horizontally laminated silt (lower part of unit 4, Fig. 3). Based on an erosive lower contact, upward increase in grain size, and stratigraphic position, these sediments are correlated to the fine grained sand to sandy silt in the lower part of unit 5 in core Assin-2 (Fig. 3), which also overlies finer sediment at an abrupt contact. This erosional event marks the beginning of Phase 5.

The influx of water responsible for depositing these units also led to the incision of a proto-Swan River channel in the northern part of the Lake Assiniboine plain (Kehew and Lord, 1987; Fig. 9e). In turn, this water spilled out of the overflow channel of Lake Assiniboine, eroded the complex of lake outlet channels below 488 m (Fig. 7a), and ultimately caused Lake Assiniboine to entrench its southern margin and drain to 434 m. Alternatively, the restricting ice dam at the southern end of the lake (Fig. 9d) may have failed. Eventually, a channel near the centre of the scoured area became the preferred drainage route and was entrenched 54 m below the former outlet of glacial Lake Assiniboine.

Several geomorphic and sedimentological features suggest that the Phase 5 drainage event was catastrophic. The

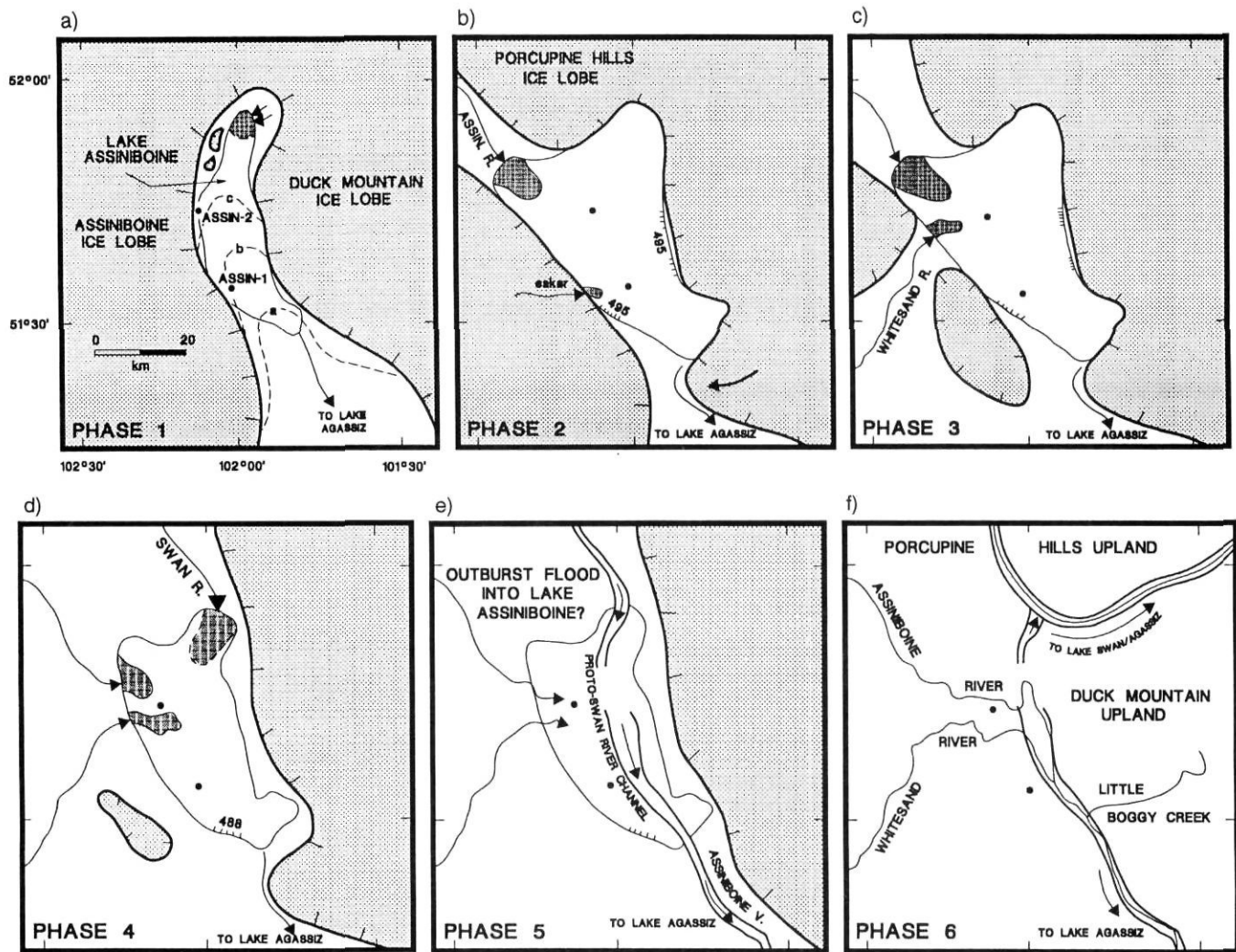


FIGURE 9. The history of glacial Lake Assiniboine. a) Phase 1: Lake Assiniboine formed in the low area between the Assiniboine and Duck Mountain Ice Lobes and "a", "b", and "c" show how the ice may have retreated. b) Phase 2: Lake level probably rose to 495 m as the southern outlet was dammed by a readvance of ice, and beaches formed (hatched lines) in the southern part of Lake Assiniboine and along the Duck Mountain Upland. Inflow sources included the Assiniboine River, which drained the Porcupine Hills area to the north of glacial Lake Assiniboine and meltwater from the ice sheet to the west where an esker is now present. Outflow to Lake Agassiz occurred in a channel at 495 m. c) Phase 3: Wastage of the Assiniboine Ice Lobe allowed the Whitesand River to flow and deposit coarse grained sediment where it entered Lake Assiniboine. d) Phase 4: A major flow entered the northern part of Lake Assiniboine through the proto-Swan River inlet from the Porcupine Hills area and caused the outlet of Lake Assiniboine to be incised. These events resulted in a decrease in lake level to 488 m and a beach (hatched line) formed in the southern part of the lake. Outflow to Lake Agassiz was established in a channel at 488 m. e) Phase 5: A second major flow entered Lake Assiniboine from the north and incised a channel at the inlet to the lake (Kehew and Lord, 1987). The inflow spilled over the outlet causing Lake Assiniboine to breach its southern margin. Incision of the Assiniboine valley 54 m below the level of the lake caused Lake Assiniboine to rapidly drain. f) Phase 6: Almost concurrent with the drainage of Lake Assiniboine, ice to the northeast retreated allowing the Swan River to incise its valley below the depth of the proto-Swan River channel. Subsequently, meltwater from the Porcupine Hills area that was carried by the Swan River valley entered glacial Lake Swan and, eventually, Lake Agassiz to the northeast. The Assiniboine and Whitesand Rivers and Little Boggy Creek flowed across the exposed basin before heading south through the Assiniboine valley.

Évolution du Lac Assiniboine, a) Phase 1: Le Lac Assiniboine s'est formé dans la partie basse située entre les lobes glaciaires Assiniboine et Duck Mountain; les tiretés « a », « b » et « c » illustrent le retrait glaciaire. b) Phase 2: le niveau a probablement atteint 495 m pendant l'obstruction de l'exutoire sud par une glace de récurrence; des plages (hachures) se sont formées dans la partie sud du Lac Assiniboine et le long des hauteurs de Duck Mountain. Entre autres provenances de l'eau: l'Assiniboine, qui drainait les Porcupine Hills au nord du Lac Assiniboine, et l'eau de fonte de l'inlandsis vers l'ouest, là où se trouve maintenant un esker. L'écoulement vers le Lac Agassiz se faisait par un chenal situé à 495 m. c) Phase 3: l'ablation du lobe glaciaire Assiniboine a permis l'écoulement de la Whitesand River et le dépôt de sédiments grossiers à l'entrée du Lac Assiniboine. d) Phase 4: un écoulement considérable ayant emprunté la Swan River primitive à partir des Porcupine Hills a envahi la partie nord du Lac Assiniboine et a provoqué l'incision de l'exutoire du Lac Assiniboine. Le niveau du lac s'est alors abaissé à 488 m et une plage (hachures) s'est formée dans la partie sud du lac. L'écoulement vers le Lac Agassiz s'est fait par un chenal situé à 488 m. e) Phase 5: un deuxième écoulement important en provenance du nord a de nouveau envahi le Lac Assiniboine et a entaillé un chenal à l'entrée du lac provoquant la formation d'une brèche au sud (Kehew et Lord, 1987). L'incision de la vallée de l'Assiniboine à 54 m sous le niveau du lac a entraîné le drainage précipité du lac. f) Phase 6: concurremment, le recul de la glace vers le nord-est a entraîné l'incision de la vallée de la Swan River plus profondément que le chenal originel. Par la suite, l'eau de fonte des Porcupine Hills transportée par la Swan River entraînait dans le Lac Swan puis dans le Lac Agassiz par le nord-est. Les rivières Assiniboine et Whitesand et le Little Boggy Creek empruntaient le bassin avant de se diriger vers la vallée de l'Assiniboine, au sud.

large channel that enters Lake Assiniboine from the north (the proto-Swan River valley) and the spillway that leaves the basin to the south (the Assiniboine valley) are similar to inflow and outflow trenches in the Lake Souris and Lake Hind basins described by Kehew and Lord (1987) and interpreted to have been the result of catastrophic flooding. In the outlet region of Lake Assiniboine (Fig. 7a) are additional features characteristic of large flows (Kehew and Lord, 1987), including boulder lag deposits, erosional residuals, and both shallow (Fig. 9a) and deeply incised channels below 488 m adjacent to the Assiniboine valley.

The geomorphology of the Assiniboine valley and at sites neighbouring the main trench downstream (Fig. 7b-d) also support a catastrophic flood origin although other sources of large flows, aside from abrupt drainage from glacial Lake Assiniboine, are possible. Because various glacial lakes may have discharged meltwater through the lower portions of the Assiniboine valley, notably through the Qu'Appelle spillway (Kehew and Teller, 1994), catastrophic flood features recognized downstream from the junction of these two valleys (Fig. 7c and 7d) cannot be attributed exclusively to a drainage event from glacial Lake Assiniboine. In fact, two erosional scarps at differing elevations in the outer zone near Virden (Fig. 7d) argues for at least two drainage events. However, because the proto-Swan River channel north of the glacial Lake Assiniboine plain does not cut across the floor of the lake basin, it appears that (1) after the final drainage of Lake Assiniboine there were no subsequent floods, either across the floor of Lake Assiniboine or along the Assiniboine valley from the lake outlet to the Qu'Appelle junction, and (2) the modern deep valley probably had formed by the end of the catastrophic overflow and drainage from the lake.

PHASE 6

The upper 0.9 m in the Assin-2 core is composed of fine grained, very well sorted, structureless sand (upper part of unit 5; Fig. 3) and is interpreted to be material reworked by aeolian processes following the final drainage of Lake Assiniboine. Today, stabilized relict dunes are scattered across the western floor of the lake. This aeolian unit is correlated to the post-drainage sediment in the Assin-1 core (upper part of unit 4), which is composed of mottled to poorly laminated silty clay (Fig. 3). These sediments in the Assin-1 core suggest that shallow, small ponds may have remained in the deepest part of the lake basin after the outburst.

Almost concurrent with the draining of Lake Assiniboine, ice in the Swan River valley must have retreated (or have been breached), otherwise the proto-Swan River would have continued to flow across the exposed floor of the Lake Assiniboine basin and have graded to the Assiniboine valley, instead of establishing its modern northeasterly route between the Duck Mountain Upland and the Porcupine Hills Upland (Fig. 9f). Entrenchment of the modern Swan River valley 30 m below the north-south trending proto-Swan River channel (Fig. 9e) reversed drainage to the north in the former inlet of Lake Assiniboine (Fig. 9f). With retreat of ice

from the lower Swan River valley, glacial Lake Swan formed (Nielsen, 1988).

Elsewhere in the basin, the Assiniboine and Whitesand Rivers, and Little Boggy Creek established meandering channels across the exposed lake floor, eventually joining to flow south through the Assiniboine valley to Lake Agassiz (Fig. 9f).

SUMMARY

Based on regional studies of ice margins (Klassen, 1975; Fenton *et al.*, 1983; Nielsen, 1988), meltwater runoff from retreating Laurentide ice first became ponded just after 11,200 BP in the interlobate region between ice on the Duck Mountain Upland and the Assiniboine Ice Lobe to the west. Within a few years, ice advanced, probably from the Duck Mountain Upland, and dammed the lake's southern outlet causing lake level to rise to at least 495 m. For about 40 varve years, inflow to the lake was supplied by glacial meltwater from ice that surrounded the basin and by the Assiniboine River to the northwest. Overflow from Lake Assiniboine may have been around an ice dam en route to Lake Agassiz via a shallow Assiniboine valley. Retreat of the active ice margin along the western side of the basin allowed the Whitesand River to enter Lake Assiniboine for about 45 varve years.

Following approximately 85 years of varve deposition, a major influx of water entered the northern part of Lake Assiniboine through the proto-Swan River inlet, causing the outlet of Lake Assiniboine to be incised and lake level to fall to 488 m. At least 20 varve years later, a second major influx through the proto-Swan River caused Lake Assiniboine to enlarge its southern outlet. As a result, Lake Assiniboine drained catastrophically through the Assiniboine valley to Lake Agassiz. The deep channel of the Assiniboine valley was incised by this outburst.

Immediately after (or concurrent with) Lake Assiniboine drainage, ice in the lower Swan River valley must have retreated and subsequent drainage from the Porcupine Hills Upland through the Swan River valley was routed to the northeast, abandoning its former southerly route into the Assiniboine basin. This meltwater entered glacial Lake Swan which, upon further ice retreat, eventually merged with or drained into Lake Agassiz. Erosion during the Moorhead low water stage of Lake Agassiz, about 10,800 to 10,000 BP (Fenton *et al.*, 1983), allowed the new Swan River to entrench its valley well below the floor of the old glacial Lake Assiniboine lake plain.

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